Impact of the melt–albedo feedback on the future evolution of the Greenland Ice Sheet with PISM-dEBM-simple

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Abstract. Surface melting of the Greenland Ice Sheet contributes a large amount to current and future sea-level rise. Increased surface melt, algae growth, debris, and dust deposition lower the reflectivity of the ice surface and thereby increase melt rates: the so-called melt–albedo feedback describes this potentially self-sustaining increase in surface melting. Here we present a simplified version of the diurnal Energy Balance Model (dEBM-simple) which is implemented as a surface melt module in the Parallel Ice Sheet Model (PISM). dEBM-simple is a modification of diurnal Energy Balance Model (dEBM), a surface melt scheme of intermediate complexity useful for simulations over centennial to multi-millennial timescales. dEBM-simple is computationally efficient, suitable for standalone ice-sheet modeling and includes a simple representation of the melt–albedo feedback. Using dEBM-simple and PISM, we find that this feedback increases ice loss until 2300 through surface warming by 60 % for the high-emission scenario RCP8.5. With an increase of 90 %, the effect is more pronounced for lower surface warming under RCP2.6. Furthermore, assuming an immediate darkening of the ice surface over all summer months, we estimate an upper bound for this effect to be +70% in the RCP8.5 scenario and a more than fourfold increase under RCP2.6. With dEBM-simple implemented in PISM, we find that the melt–albedo feedback is an essential contributor to mass loss in dynamic simulations of the Greenland Ice Sheet under future warming.

1 Introduction

The Greenland Ice Sheet is currently one of the main contributors to sea-level rise (Frederikse et al., 2020). Roughly 35% of the observed mass loss during the last 40 years is attributed to changes in surface mass balance and 65% of the mass loss is due to an increase in discharge fluxes (Mouginot et al., 2019). Overall, the contribution of changes in surface mass balance is expected to increase with ongoing warming (Shepherd et al., 2020).

Observations show that the surface of the Greenland Ice Sheet has been darkening over the last decades (He et al., 2013; Tedesco et al., 2016), and projections show that it is likely to darken further with increasing warming (Tedesco et al., 2016). Changes in albedo are driven by melt, the retreat of the snow line, black carbon, dust, and algae growth (Cook et al., 2020; Williamson et al., 2020; Box et al., 2012; Box, 2013; Box et al., 2017; Tedstone et al., 2017, 2020; Ryan et al., 2019). In

5 particular the dark zone in the south-west of the Greenland Ice Sheet is subject to increased darkening, where ice-albedo values reach values as low as 0.27 due to surface water and impurities at the surface (for comparison, clean ice has typically an albedo between 0.45 and 0.55) (Ryan et al., 2019). As darker snow and bare ice absorb more radiation, thereby increasing melt rates, these processes could trigger a positive feedback mechanism: surface darkening increases melting, which in turn can lead to further darkening (Stroeve, 2001). Studies suggest a positive feedback mechanism between microbes, minerals, and melting,

10 where algae-induced melting releases ice-bound dust, which in turn increases glacier algal blooms, leading to more melt (Di Mauro et al., 2020; McCutcheon et al., 2021). This melt–albedo feedback is usually interrupted by winter snow accumulation and snow events in summer (Gardner and Sharp, 2010; Noël et al., 2015). In the light of recent extreme melting events as in 2010 (Tedesco et al., 2011), 2012 (Nghiem et al., 2012) or 2019 (Tedesco and Fettweis, 2020), where large parts of the surface area were covered by melt water and therefore darker than usual, it is important to model the response of the ice sheet to such

15 large-scale changes in albedo.

To assess the influence of the atmosphere on the surface mass balance of ice sheets a range of models is available and typically used: from process-based snow pack models coupled to regional climate models, which explicitly compute the regional climate and energy fluxes in the snow and at the ice surface (Fettweis et al., 2013, 2017; Noël et al., 2015; Langen et al., 2015; Niwano et al., 2018; Krapp et al., 2017), to simpler parameterizations like the positive degree day (PDD) models (e.g. Reeh,

20 1991). Regional climate models, for example, can be coupled with an ice-sheet model to compute interactions of the ice and the atmosphere while explicitly resolving all relevant feedbacks (Le clec'h et al., 2019). Since this is computationally expensive, often a simpler approach is required in order to run simulations over centuries to millennia or large ensembles of simulations. In such cases, the surface mass balance is typically calculated from near-surface air temperatures with a positive degree day approach (Wilton et al., 2017; Aschwanden et al., 2019; Rückamp et al., 2019), which is computationally much less expensive

25 but lacks the direct contribution of shortwave radiation and albedo to melting. The insolation–temperature–melt equation is one of the few examples, which uses explicit albedo and insolation on long time scales (van den Berg et al., 2008; Robinson et al., 2010).

The recent development of the diurnal energy balance model dEBM presented by Krebs-Kanzow et al. (2020) (with a simpler version introduced in Krebs-Kanzow et al. (2018)) is computationally efficient, works well for the Greenland Ice Sheet, and

30 can represent melt contributions from changes in albedo as well as seasonal and latitudinal variations of the diurnal cycle. In the Greenland Surface Mass Balance Model Intercomparison Project (Goelzer et al., 2020), dEBM shows a good correlation with ice core data, air-borne radar and PROMICE data and is among the models which compare the closest with observed integrated mass losses from 2003-2012 (Fettweis et al., 2020). Thus it fills the gap between a process-based snow pack model coupled to a regional climate model and a simple and efficient temperature-index approach such as PDD.

To this end, we here expand the Parallel Ice Sheet Model (PISM) (the PISM authors, 2018; Winkelmann et al., 2011; Bueler and Brown, 2009) by the surface module dEBM-simple, which includes melt driven by changes in albedo, in order to explore their effects on the future ice evolution. In addition, we introduce parameterizations of albedo and atmospheric transmissivity to make it possible to run the model in standalone, prognostic mode (see Section 2). In particular the nonlinear albedo–melt

5 relation (see Section 2.3.2) serves as an approximation to the melt–albedo feedback and allows to estimate its importance. We compare the model against regional climate model simulations from MAR and find a good fit (Sect. 3). We explore the minimal and maximal contribution of the melt–albedo feedback to future mass losses and test the effect of albedo changes on future mass loss under RCP2.6 and RCP8.5 warming (Sect. 4). The results are discussed in Sect. 5.

2 Methods

10 We first present the Parallel Ice Sheet Model PISM, then describe the diurnal Energy Balance Model as introduced in Krebs-Kanzow et al. (2018) and its implementation in PISM. To be able to run the model in standalone, prognostic mode, we introduce parameterizations of the surface albedo and transmissivity in Sections 2.3.2 and 2.3.1 (see Appendix A for more detail). In the last two subsections, we describe the spin-up of PISM for the Greenland Ice Sheet and the experiments conducted in the next sections.

15 ### 2.1 Ice-sheet model PISM

PISM is a thermomechanically coupled ice-sheet model which uses a superposition of the shallow-ice approximation (SIA) for slow-flowing ice, and the shallow shelf approximation (SSA) for fast-flowing ice streams and ice shelves (Bueler and Brown, 2009; Winkelmann et al., 2011; the PISM authors, 2018). PISM was shown to be capable of reproducing the complex flow patterns evident in Greenland's outlet glaciers (Aschwanden et al., 2016).

20 The SSA basal sliding velocities are related to basal shear stress via a power law with a Mohr–Coulomb criterion that relates the yield stress to parameterized till material properties and the effective pressure of the overlaying ice on the saturated till (Bueler and Pelt, 2015). We use a non-conserving simple hydrology model that connects the till water content to the basal melt rate (Bueler and van Pelt, 2015). The internal deformation of the ice is described by *Glen's flow law* with the flow exponent $n = 3$ for both, SIA and SSA flow and with the enhancement factors $E_{SSA} = 1$ and $E_{SIA} = 1.5$ for SSA and SIA flow

25 respectively.

Using PISM, we first create an initial configuration of the Greenland Ice Sheet under present-day climate conditions. Then we run a suite of experiments to validate dEBM simple for present-day as well as to test the role of insolation and temperature melting in future warming scenarios.

In this manuscript we concentrate on the changes in the surface mass balance, which is modelled using the newly imple-

30 mented dEBM-simple. The atmospheric conditions, namely the monthly 2D temperature and precipitation fields, are read in as input fields. The precipitation fields remain fixed and the share of snowfall and rain is determined from the local near-surface air temperature. We neglect effects from changing ocean temperatures, thus the sub-shelf melting is constant in space and time

at 0.047 m/yr. Also, calving is not modeled explicitly, but induced by a fixed calving front at its present-day location based on Morlighem et al. (2017), thus changes in mass losses from ice-ocean interaction are not considered here. Isostatic adjustment of the bedrock is not considered here. All experiments were run on a 4.5 km horizontal grid with a constant vertical resolution of 16 m.

2.2 Adapted diurnal energy balance model dEBM-simple

For the simple version of the diurnal energy balance model (dEBM-simple) we follow the parametrization as laid out by Krebs-Kanzow et al. (2018). The melt equation reads

$$M = \frac{\Delta t_\Phi}{\Delta t \rho_w L_m} \left(\tau_\alpha (1 - \alpha_s) \bar{S}_\Phi + c_1 T_{\text{eff}} + c_2 \right), \tag{1}$$

with fresh water density ρ_w, latent heat of fusion L_m, surface albedo α_s, atmospheric transmissivity τ_α. The parameters describing the effective temperature influence on melting c_1 and the melt intercept c_2 are estimated from MAR v3.11 simulations (Fettweis et al., 2017), see Section 3. The values used here are given in Table A2. dEBM is based on the assumption that melting occurs only during daytime, when the sun is above an elevation angle Φ, which is estimated to be constant in space and time $\Phi = 17.5°$. The time period of a day when the sun is above the elevation angle Φ is denoted by Δt_Φ. The length of a day is Δt and the fractional time that the sun is above the elevation angle Φ is given by:

$$\frac{\Delta t_\Phi}{\Delta t} = \frac{h_\Phi}{\pi} = \frac{1}{\pi} \frac{\sin \Phi - \sin \varphi \sin \delta}{\cos \varphi \cos \delta} \tag{2}$$

with h_Φ being the hour angle when the sun has an elevation angle of at least Φ, δ being the solar declination angle and φ the latitude. The incoming radiation over the time Δt_Φ (when the sun is above the declination angle Φ) drives the melting. It is obtained from the insolation at the top of the atmosphere (TOA), $\bar{S}_\Phi$, and the parameterized transmissivity τ_α (see equation (6)).

In addition, the temperature-dependent melting is not a function of the air temperature directly as in, e.g., Pellicciotti et al. (2005); van den Berg et al. (2008), but a function of the cumulative temperature exceeding the melting point in a given month T_{eff} as in Krebs-Kanzow et al. (2018, 2020).

$$T_{\text{eff}}(\bar{T}, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} \int_0^\infty dT \, T \exp\left(-\frac{(T - \bar{T})^2}{2\sigma^2} \right) \tag{3}$$

Here, T is the fluctuating daily temperature, $\bar{T}$ is the monthly average temperature, which is used as an input, and σ is the standard deviation of the temperature. The melting point is at $0\,°C$.

2.3 Implementation of dEBM-simple in PISM

The diurnal energy balance model is implemented in PISM as a climatic mass balance module. It takes the local near-surface air temperature and the precipitation as an input and computes the local climatic mass balance. The shortwave downward radiation and the broadband albedo are not needed as inputs, as they are parameterized internally, with the possibilty to use other orbital

parameters than the present day values. The melt module is evaluated at least weekly, independent of the adaptive time step used for the ice dynamics in PISM. The amount of melt is balanced with refreezing and snowfall before the surface mass balance is aggregated over the adaptive time steps in PISM. The aggregated values feed into the update of the ice geometry. If a run is started without knowledge about melting in the previous time step, the albedo is assumed to be at the fresh snow value

5 everywhere on the ice sheet or can be read in from an input file. In line with Krebs-Kanzow et al. (2018), no melting is allowed below $-6.5°\text{C}$ even if the insolation alone would be sufficient to cause melting.

2.3.1 Parametrization of shortwave downward radiation

The shortwave downward radiation is computed from the top of the atmosphere insolation and a linear model of the transmissivity of the atmosphere. Daily average TOA insolation $\bar{Q}^{\text{day}}$ is computed from

$$\bar{Q}^{\text{day}} = \frac{S_0}{\pi} \left(\frac{\bar{d}}{d}\right)^2 (h_0 \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin h_0), \tag{4}$$

where $S_0 = 1367\,\text{W/m}^2$ is the annual mean of the total solar irradiance (solar constant), $\bar{d}$ is the annual mean distance of the earth to the sun, d is the current distance, φ is the latitude, δ is the declination angle, and h_0 is the hour angle of sunrise and sunset. The average TOA insolation during the daily melt period $\bar{S}_\Phi$ is given by

$$\bar{S}_\Phi = \frac{S_0}{\Delta t_\Phi \pi} \left(\frac{\bar{d}}{d}\right)^2 (h_\Phi \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin h_\Phi) \tag{5}$$

15 Under present day conditions the declination angle δ and the sun-earth distance d are approximated with trigonometric expansions depending on the day of the year, see Liou (2002, Chapter 2.2.).

To scale the insolation to the ice surface, we assume that the transmissivity of the atmosphere depends only on the local surface altitude in a linear way (similar to Robinson et al. (2010)). The linear fit for the shortwave downward radiation from TOA insolation is obtained from a linear regression of MAR v3.11 data averaged over June, July and August from 1958 to

20 2019 (see Appendix A2 and Figure A2). The transmissivity is given by:

$$\tau_\alpha = a + b \cdot z, \tag{6}$$

where a and b are parameters (here $a = 0.57$ and $b = 0.037\text{km}^{-1}$) and z is the surface altitude in km. The approach to calculate shortwave downward radiation is further described in Appendix A2, in particular it is described how TOA conditions different than present-day, e.g. during the Eemian, can be modeled.

25 ### 2.3.2 Albedo parametrization

PISM-dEBM-simple allows to read in the albedo field as an input. However, in order to keep the input requirements for a standalone version of the model minimal and to allow for a melt-dependent albedo, a simple albedo parametrization is implemented. Regional climate models such as MAR or RACMO use a snowpack model to determine the albedo (van Dalum et al., 2020). Snow albedo there is explicitly calculated based on snow grain size, cloud optical thickness, solar zenith angle

and impurity concentration in snow or parameterized. Ice albedo there can be explicitly calculated as a function of ice density, time of the day, solar angle, spectrum of the solar radiation etc. Here, in contrast, albedo is paramaterized in an ad-hoc way as a function of the melt in the last (weekly) timestep. As the time step in the climatic mass balance module is typically smaller than the adaptive ice-dynamics time-step, and the temporal resolution of the 2d air-temperature input, this approach allows for

5 several iterations of the melt-dependent albedo under otherwise same conditions.

The corresponding parameters are fitted using MAR data. The advantage of this approach is that it requires no further information in PISM (e.g., a fully resolved firn-layer) but still allows us to capture melt processes. In this approach, the albedo decreases linearly with increasing melt from the maximal value $\alpha_{\max} = 0.81$ (close to the fresh-snow albedo) for regions with no melting to $\alpha_{\min} = 0.47$ (close to the bare-ice albedo). The albedo cannot drop below the value of $\alpha_{\min}$.

10 $$\alpha_s = \max[\alpha_{\max} - c \cdot M, \alpha_{\min}] \qquad (7)$$

The slope $c = -0.025$ yr/m is estimated from MAR data (see appendix Figure A1 and Section A1). We will later on test the sensitivity of the melting to the parameters.

2.4 Initial state

All simulations are started from a spun-up state and run with full ice dynamics (SIA and SSA as well as temperature evolution

15 and a thermomechanical coupling). For the spin-up the procedure detailed in Aschwanden et al. (2019) is used: a temperature anomaly is applied over the last 125 ka to the climatological mean (1971 to 1990 monthly averages) of the 2D temperature field of MAR v3.9 in order to obtain a realistic temperature distribution within the ice. Ice geometry and bedrock topography are from BedMachine V3 (Morlighem et al., 2017). Basal heat flux is obtained from Maule (2005). In the simulations, surface temperatures are scaled with surface elevation (atmospheric temperature lapse rate of -6 K/km) to include the melt–elevation

20 feedback in the simulations. Precipitation is not scaled with changing temperature. The spin-up is performed using the more conventional positive-degree day model.

The thickness and velocity anomalies of the initial state at the end of the spin-up are detailed in Beckmann and Winkelmann (submitted).

2.5 Calibration experiments

25 To calibrate the model parameters and test the parameterizations, we perform diagnostic experiments over the period between 1958 and 2019. In order to disentangle the surface module from indirect effects of ice dynamics, e.g. dynamic thinning and thus a temperature increase through the temperature lapse rate, changes in the ice topography are suppressed in these diagnostic experiments. Monthly MAR v3.11 near-surface air temperature and precipitation fields from 1958 to 2019 are used as atmosphere input.

30 The sensitivity to Eemian insolation values is tested in an analogous experiment where only the orbital parameters, which determine the top of the atmosphere insolation, are changed.

2.6 Warming and darkening experiments over the next centuries

Here, we describe the series of experiments which are performed to assess the impact of the melt–albedo feedback onto the mass losses of the Greenland Ice Sheet. All experiments start from the same initial state, described in Sect. 2.4 and run over the period from 2000 to 2300. Melt rates are calculated by PISM-dEBM-simple using periodic monthly temperature fields given

5 by the climatological mean from 1971 to 1990. The regional climate model MAR v3.11 was forced with ERA reanalysis data (ERA-40 from 1958-1978 and ERA-5 after) Amory et al. (2020). In the warming experiments, scalar temperature anomalies are applied uniformly over the entire ice sheet.

In addition to forced temperature changes, the local near-surface air temperature adapts to topography changes of the ice sheet with a lapse rate of -6 K / km, thus taking the melt–elevation feedback into account. Note that in all experiments changes

10 in albedo do not feed back onto the atmosphere, in particular albedo changes do not affect near-surface air temperatures.

We perform the following experiments:

- **Ctrl:** Control run without darkening or temperature anomalies, using the parameters from Table A2 consistent with the present day experiments presented in Section 3.

- **RCP2.6** and **RCP8.5:** Similar to Ctrl, with a scalar temperature anomaly from the RCP2.6 and the RCP8.5 scenarios of

15 the IPSL-CM5A-LR model (Dufresne et al., 2013), respectively, which is one of four CMIP5 models extended until 2300. The scalar temperature anomaly was obtained by averaging the monthly near-surface temperature over the Greenland Ice Sheet and computing the anomalies to the average yearly cycle of 1971-1990 over the same spatial domain.

- **Ctrl α_{1990}, RCP2.6 α_{1990},** and **RCP8.5 α_{1990}**: Control and warming experiments with a fixed yearly cycle of albedo values instead of the melt-dependent parameterization. The 2 dimensional albedo fields are obtained from monthly

20 averages from the MAR v3.11 data, averaged over the period before 1990. Scalar temperature anomalies as detailed above in RCP2.6, RCP8.5.

- **Ctrl α_{dark}, RCP2.6 α_{dark},** and **RCP8.5 α_{dark}**: In these experiments the albedo over the entire ice sheet is lowered to the bare ice value of 0.47 during the summer months June, July and August. During all other months the albedo parametrization (with the optimized values as described in Appendix A1) is used to compute the albedo. Scalar temper-

25 ature anomalies as detailed above in RCP2.6, RCP8.5.

- **Ctrl α_{ls}, RCP2.6 α_{ls},** and **RCP8.5 α_{ls}**: The slope of the albedo parametrization is decreased to half the optimal value (which correspond to -0.013 yr/m). Thus the bare ice value of the albedo is reached at melt rates of 28 m/yr, (compared to 14 m/yr with the optimal value for the slope). Scalar temperature forcing for the RCP experiments as described above.

- **Ctrl α_{hs}, RCP2.6 α_{hs},** and **RCP8.5 α_{hs}**: The slope of the albedo parametrization is increased to twice the optimal value

30 (which correspond to -0.05 yr/m). Thus the bare ice value of the albedo is reached at melt rates of 7 m/yr, (compared to 14 m/yr with the optimal value for the slope). Scalar temperature forcing for the RCP experiments as described above.

- **Ctrl $\alpha_{\mathbf{min}}$x, RCP2.6 $\alpha_{\mathbf{min}}$x, and RCP8.5 $\alpha_{\mathbf{min}}$x**: The lower limit for albedo values is reduced from the standard value of 0.47 to x=0.4 and x=0.3. The slope of the albedo parametrization remains unchanged, but albedo values decrease further for melt rates above 14 m/yr until the new minimal albedo value is reached. Scalar temperature forcing for the RCP experiments as detailed above.

- **Ctrl $T_{\mathbf{noLR}}$, RCP2.6 $T_{\mathbf{noLR}}$, and RCP8.5 $T_{\mathbf{noLR}}$**: Experiments analogous to Ctrl, RCP2.6 and RCP8.5, but neglecting the atmospheric temperature lapse rate. Thus the local temperature is independent of the ice-sheet topography and the representation of the melt–elevation feedback is interrupted.

The α_{1990} experiments use a constant albedo cycle, and therefore suppress the adaptation of albedo to increased melt rates under warming. They are used to estimate future ice loss without the melt–albedo feedback. The α_{dark} experiments represent
10 an extreme scenario, assuming that the whole ice surface will be snow free or covered with melt water during the months June, July and August in each year. This is not a realistic scenario but rather an upper limit to the possible impact of albedo changes on ice losses. The α_{ls}, α_{hs} and α_{min} experiments explore the uncertainty from the albedo parameterization. Doubling the slope to -0.05 yr/m leads to a steeper decrease in albedo with increasing melt rates, which is closer to the conditions in August (see Appendix Figure A1). Assuming that in the future the melting period over the Greenland Ice Sheet is longer and
15 therefore the conditions we observe in August might be more characteristic over the melting period, justifies to explore the impact of an increased sensitivity in the α_{hs} experiments. However, in this approach the minimal albedo for bare ice remains at 0.47, and is therefore reached with melt rates of 7 m/yr (instead of 14 m/yr in the standard parameterization). Halving the slope to -0.013 yr/m explores the lower boundary of albedo-melt sensitivity (see Figure A1) in the α_{ls} experiments. In the α_{min} experiments, we test the influence of a reduced minimum albedo, as observed today in the dark zone of the Greenland Ice
20 Sheet.

3 Validation for the Greenland Ice Sheet

In this section, we validate the dEBM-simple melt for present-day conditions and show as and example melt rates with Eemian insolation.

3.1 Present-day melt rates

25 As described in Section 2.5, we use historic and present day experiments to optimize for the melt parameters in equation (1). We compare the resulting modeled melt over the historic period with melting modeled by MARv3.11 in Figure 1. The experimental setup is described in Section 2.5. Note that here the evolution of the ice-sheet topography is suppressed, that is the melt rates are calculated over a fixed geometry corresponding to present day.

Due to the parameterization of the albedo and the transmissivity (and thus the shortwave downward radiation) detailed in
30 Section 2.3 and in Table A2, the parameters of the dEBM-simple model are adjusted from Krebs-Kanzow et al. (2018). The chosen dEBM-simple parameters c_1 and c_2 (see Table A2) minimize the product of spatial and temporal root mean square error
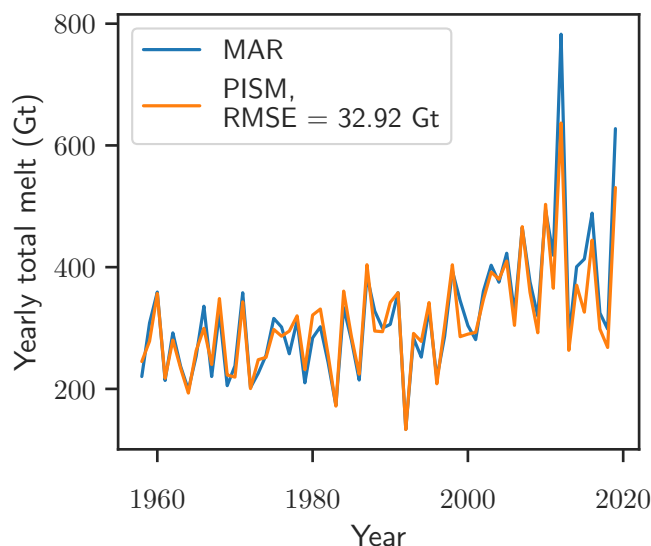
Figure 1. Comparison of annual total melt of the Greenland Ice Sheet as calculated with MAR v3.11 and PISM-dEBM-simple. The diagnostic simulation with PISM-dEBM-simple (orange line) is performed using monthly MAR 2D temperature fields as forcing. The albedo α_s is parameterized with the local melt rate m as $\alpha_s = 0.82 - 0.025\,\mathrm{yr/m} \cdot m$ and the shortwave downward radiation is approximated by the top of the atmosphere radiations and the transmissivity τ_α parameterized with surface altitude z as $\tau_\alpha = 0.037\,\mathrm{km^{-1}} \cdot z + 0.57$. The root mean square difference between the PISM-dEBM-simple simulation and total melt as given by MAR (blue line) is 32.92 Gt.

over the whole period from 1958 to 2019 while using the parametrizations for albedo and shortwave downward radiation. The temporal root mean square error is computed from a comparison of total yearly melt (see Figure 1) and the spatial root mean square error is computed from a comparison of the 2D fields of summer (JJA) melt rates averaged over the whole period (see Figure 2).

5   Yearly total melt computed with PISM follows the MAR data closely (see Figure 1). That extreme melt years such as 2012 and 2019 are underestimated can be explained by the parametrization of shortwave downward radiation, which neglects temporal variability in the cloud cover, one of the drivers of recent mass loss in Greenland (Hanna et al., 2014; Hofer et al., 2017). We also test dEBM-simple with shortwave downward radiation and albedo from MAR directly. Figure A3 shows, that in this case the extreme melt in 2019 is better captured, while melting in 2012 is still underestimated.

10   As Figure 2 shows, melt is generally overestimated in June, at the beginning of the melt season and underestimated as the melt season progresses. In July dEBM-simple underestimates melt mostly at the western margin, where ablation is highest. In August, toward the end of the melt season, melt is systematically underestimated by the dEBM-simple module.

The model is able to capture melt patterns of the Greenland ice sheet over the historic period between 1958 - 2019 with a root mean square error of 32.92 Gt for the yearly total melt and an average root mean square error of 0.36 m W.E./yr for
15   the local summer melt rates. Overall, the skill of the PISM-dEBM-simple model under present-day conditions and using high
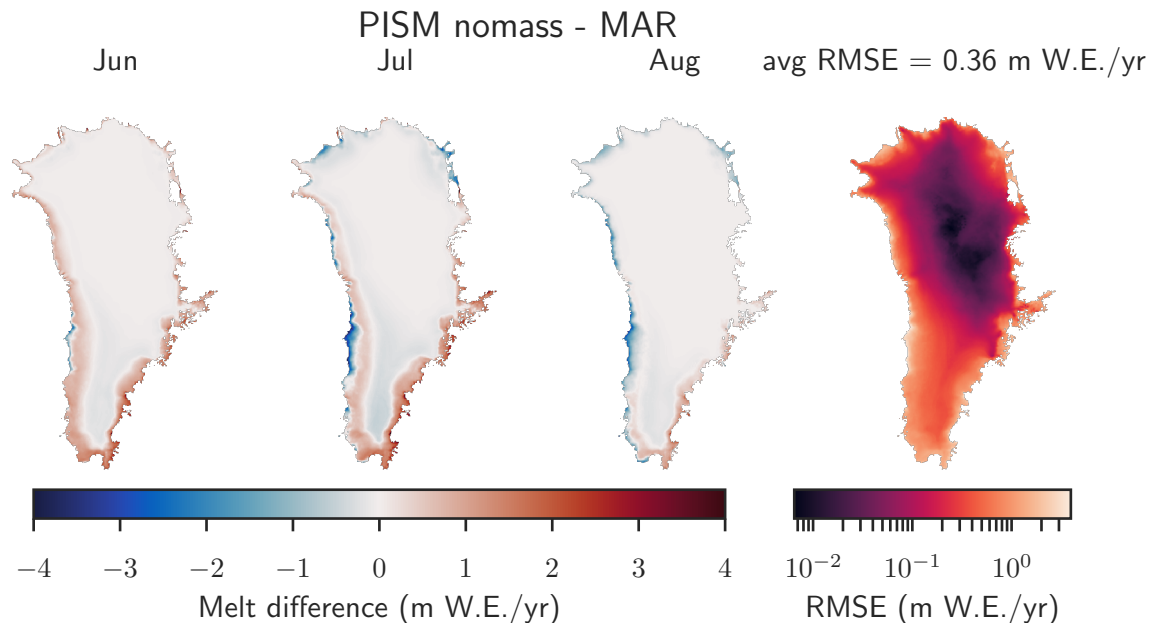
Figure 2. Local differences between the monthly averaged June, July, and August melt rates as diagnosed with PISM-dEBM-simple compared to MAR. The PISM simulation uses monthly 2D temperature fields from MAR as forcing and parametrizes albedo and shortwave downward radiation as detailed in 2.3.1 and 2.3.2. Positive numbers mean that PISM overestimates the melt and negative numbers mean that PISM underestimates the melt. The local root mean square error averaged over June, July and August from 1958-2019 is shown in the right plot. The spatial average of the RMSE is 0.36 m/yr.

resolution forcing from MAR is similar to the skill of the dEBM model (Krebs-Kanzow et al., 2020). Compared to MAR, dEBM revealed a RMSE of 27Gt for the annual mean 1979-2016 SMB in an experiment which was forced with reanalysis data (pers. com.). However dEBM better reproduces extreme years such as 2012 as this version also accounts for changes in the atmospheric emissivity and transmissivity, caused by changes in the cloud cover, as drivers of melt, and is therefore better

5   suited to represent melt-events such as in 2012. Furthermore dEBM computes the refreezing on the basis of the surface energy balance.

3.2 Sensitivity to Eemian solar radiation

The dEBM approach together with the approximations for albedo and transmissivity allows to include changing orbital parameters for simulations on paleo timescales. Here we use as an example the orbital parameters corresponding to the Eemian, 125

10   ka before present, with the eccentricity $e = 0.0400$, the obliquity $\varepsilon = 23.79°$ and the longitude of the perihelion $\omega = 307.13°$. The insolation at the top of the atmosphere is then calculated as detailed in Section A1. We use the present day topography for
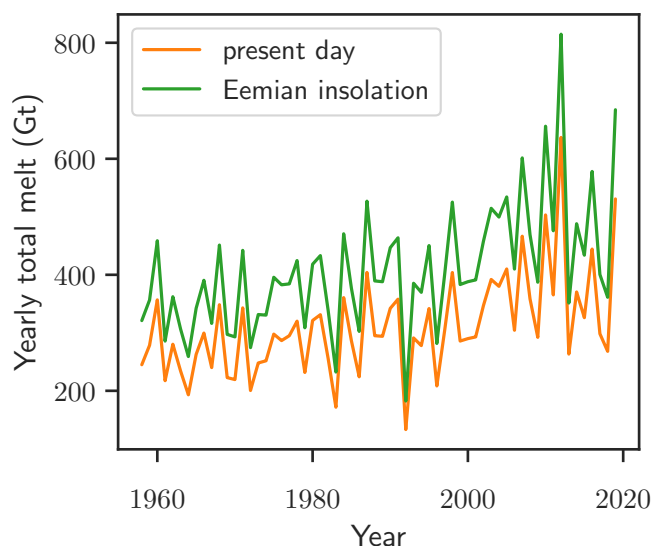
Figure 3. Comparison of Eemian vs. present-day insolation in dEBM simple Yearly total melt of the Greenland Ice Sheet as diagnosed with PISM-dEBM-simple under present day insolation (orange) and Eemian insolation (green). The diagnostic simulation with PISM were performed using monthly MAR 2D temperature fields as forcing and the parameterizations for shortwave downward radiation and albedo mentioned in the text.

the diagnosis of melt rates and keep the surface air temperature fields unchanged from the previous experiment (MAR v3.11 in the period of 1958-2019).

The increase in solar radiation leads to increased melt, as seen in Figure 3. The inter-annual variability in yearly total melt is very close to the historic variability, mainly driven by inter-annual temperature changes. Averaged over the whole time period
5 (1958-2019) the yearly total melt increases by 98 Gt/yr, which corresponds to a relative increase of 31%. This is in line with findings of Van De Berg et al. (2011), who find that Eemian insolation alone leads to 40 Gt/yr increase in runoff compared to present day and to 113 Gt/yr increase in runoff when compared to preindustrial values.

4   Influence of the melt–albedo feedback on Greenland's ice loss under future warming

Here we analyse, how changes in albedo may impact the melt rates and the ice losses of the Greenland Ice Sheet under
10 the greenhouse gas emission scenarios RCP2.6 and RCP8.5. In particular we focus on the melt–albedo feedback, and on the additional ice losses driven by changes in albedo. The experiments are motivated and described in detail in Section 2.6. The volume of the ice sheet and the mass losses until the years 2100 and 2300 due to the respective warming scenarios are summarized in Table 1.
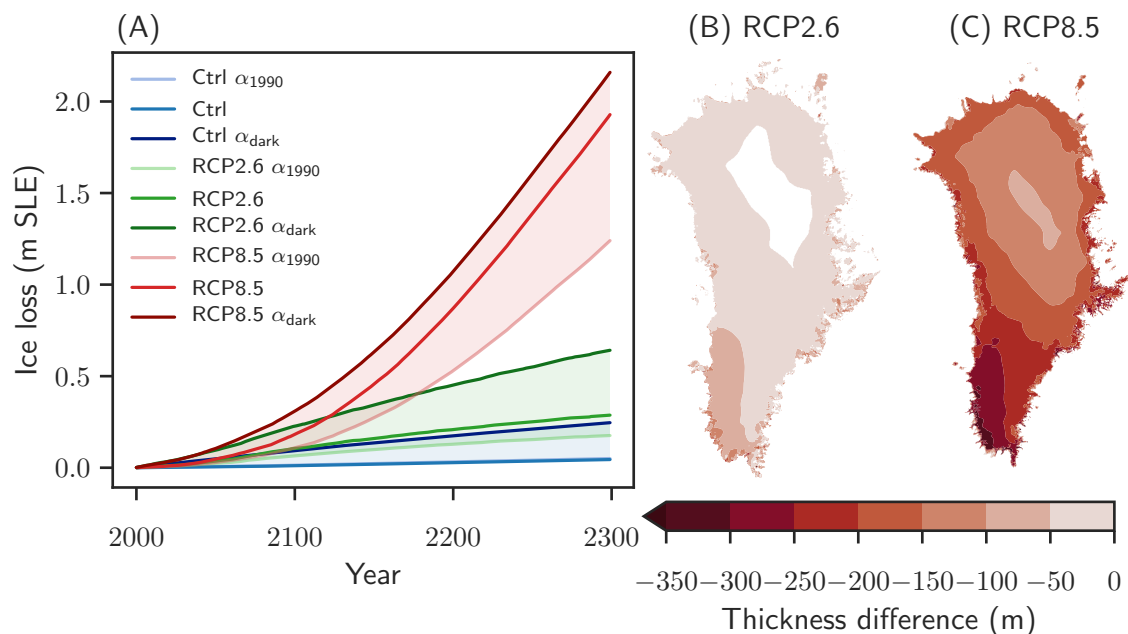
Figure 4. Influence of the melt–albedo feedback on Greenland's ice loss under future warming. The scenarios consist of a control experiment (blue), and temperature forcing with RCP2.6 (green) and RCP8.5 (red). (A) Ctrl, RCP2.6, RCP8.5: ice loss between 2000 and 2300 modelled with PISM-dEBM-simple using the standard parameters and the respective temperature forcing. α_{1990}: ice loss for the respective temperature forcing with the respective temperature forcing with monthly albedo fixed to the average pre-1990 values, thereby interrupting the melt–albedo feedback. α_{dark}: ice loss with the respective temperature forcing with summer albedos (June, July, August) set to the bare-ice value over the whole ice sheet. This yields an upper limit of ice losses driven by albedo changes. Panel (B) and (C) show the ice thickness difference between the lower bound experiments α_{1990} and the standard experiments for RCP2.6 (B) and RCP8.5 (C) in the year 2300.

4.1 Ice losses under warming without the melt–albedo feedback

Experiments with a fixed monthly albedo interrupt the melt–albedo feedback and allow to explore the lower bound of ice-losses due to warming. As described in Section 2.6, in the α_{1990} experiments the monthly albedo is fixed to an average yearly cycle given by the pre-1990 values in MARv.3.11. In consequence the insolation related melt, as given by the first term of Equation
5 (1), remains constant or even decreases due to decreasing transmissivity of the atmosphere, and only the temperature dependent term increases due to the warming.

In this scenario, the Ctrl α_{1990} experiment remains constant in volume, while the RCP2.6 α_{1990} shows 5.2 cm ice loss until 2100 and 12.6 cm until 2300. In the RCP8.5 α_{1990} experiment the ice losses amount to 9.8 cm until 2100 and to 119 cm until 2300 (see Figure 4). The mass loss until 2100 is in line with the estimate of 9 ± 5 cm in the community-wide ISMIP6
10 projections (Goelzer et al., 2020). Note that in contrast to ISMIP6, the ocean driven melting remains constant, even under
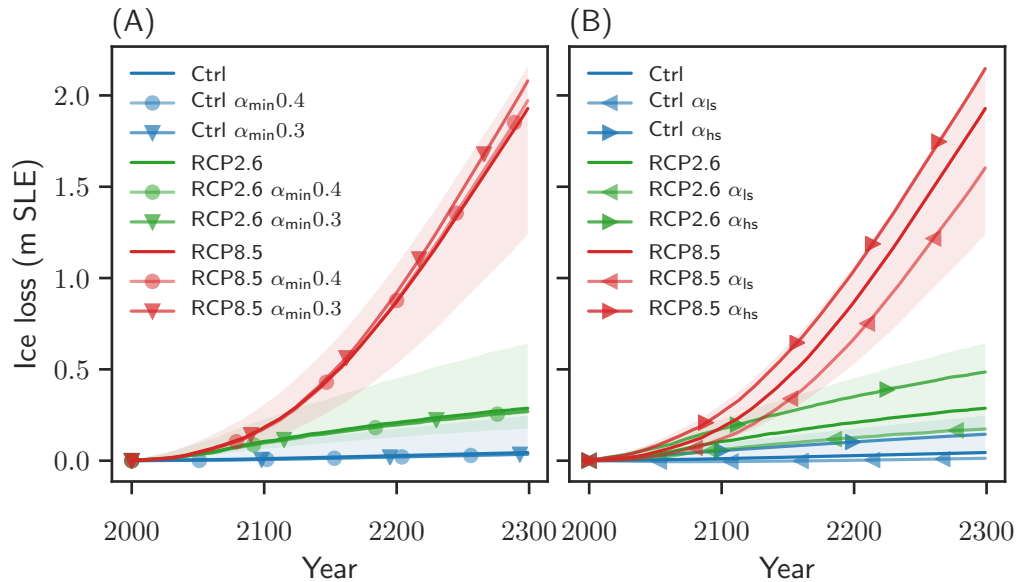
Figure 5. Uncertainty of albedo-change driven ice loss. Ice losses of the Greenland ice sheet under the Ctrl, RCP2.6, and RCP8.5 sceanrios, exploring the effect of different albedo sensitivities, as described in detail in Sect. 2.3.2 and Figure A1. Shaded regions correspond to the corridor between lower and upper bound for ice losses, as shown in Figure 4. (A) Ice losses with variations in the minimal value for albedo. Lower α_{min} corresponds to darker bare-ice. (B) Ice losses with variation in the slope of the albedo parametrization. α_{ls} experiments use a lower slope (half of the standard value), thus the sensitivity of albedo to melt is reduced. α_{hs} experiments use a higher slope (double of the standard value), thus increasing the sensitivity of albedo to melt.

increased temperatures, and there is no glacier retreat due to ice-ocean interactions. But, also the mitigating effect of an precipitation increase under a warmer climate is also missing.

4.2 Increased ice loss through the melt–albedo feedback

In the following we present the results for ice loss with PISM-dEBM-simple, taking into account the melt–albedo feedback
5 through the melt-dependent albedo parameterizations as described in Section 2. In the control simulation Ctrl, without temperature forcing or artificial darkening, the ice sheet is stable in volume on the timescale of 300 years.

In the RCP2.6 simulations, the moderate increase in temperatures leads to a approximately linear decline in ice-volume with an ice loss of 9.4 cm until 2100 and 24.3 cm until 2300. This is an increase in ice loss of +82 % in 2100 and +93 % in 2300 in comparison to the simulation without melt-alebdo feedback α_{1990} , see Fig. 4 and Table 1. The RCP8.5 simulations show
10 a strong and non-linear decline in ice-volume, with ice losses of 16.8 cm in 2100 and 1.88 m in 2300. This corresponds to a relative increase of +80 % and +58 % respectively due to the melt–albedo feedback. The relative contribution of the melt–albedo feedback to ice loss keeps increasing with time for the RCP2.6 experiment, while it becomes less important with time

Table 1. Sea-level relevant volume (in m sea-level rise equivalent) and mass loss (in cm sea-level rise equivalent). All values are relative to the respective control simulation. Only α_{dark} simulations are given in absolute values, since the Ctrl α_{dark} is an extreme scenario which does not qualify as a control experiment.

Experiments	Volume (m SLE)		ΔVolume (cm SLE)	
	2100	2300	2100	2300
Ctrl α_{1990}	7.59	7.55	-	-
Ctrl	7.59	7.55	-	-
Ctrl α_{dark}	7.51	7.35	8.3	20.1
Ctrl α_{ls}	7.60	7.59	-	-
Ctrl α_{hs}	7.54	7.45	-	-
Ctrl $\alpha_{\text{min}}0.4$	7.59	7.56	-	-
Ctrl $\alpha_{\text{min}}0.3$	7.59	7.56	-	-
RCP2.6 α_{1990}	7.53	7.42	5.2	12.6
RCP2.6	7.49	7.31	9.4	24.3
RCP2.6 α_{dark}	7.37	6.96	21.4	59.7
RCP2.6 α_{ls}	7.54	7.43	6.7	16.0
RCP2.6 α_{hs}	7.42	7.11	11.9	34.1
RCP2.6 $\alpha_{\text{min}}0.4$	7.50	7.33	9.0	23.3
RCP2.6 $\alpha_{\text{min}}0.3$	7.50	7.33	9.2	23.5
RCP8.5 α_{1990}	7.49	6.36	9.3	119.0
RCP8.5	7.42	5.67	16.8	188.4
RCP8.5 α_{dark}	7.29	5.44	29.3	211.5
RCP8.5 α_{ls}	7.48	6.00	12.2	159.0
RCP8.5 α_{hs}	7.34	5.45	20.5	200.2
RCP8.5 $\alpha_{\text{min}}0.4$	7.43	5.63	16.4	193.7
RCP8.5 $\alpha_{\text{min}}0.3$	7.42	5.52	17.0	204.4

for the RCP8.5 experiment. However, in absolute terms the melt–albedo feedback still contributes almost 70 cm SLE mass loss in the RCP8.5 experiment until the year 2300.

We compare these values with the influence of the melt–elevation feedback, see Fig. C1. This feedback is weaker, it increases the ice loss by 18 % and 13 % in the RCP2.6 and RCP8.5 simulations respectively.

5   The melt–albedo feedback is particularly important in the south of Greenland, where the insolation averaged over the daily melt period $\bar{S}_\Phi$ (see Eq. (1)) is highest. Until the year 2300 it initiates up to 100 m additional thinning in the South-West for the RCP2.6 scenario compared to RCP2.6 α_{1990} (Figure 4 (B)). In the RCP8.5 experiment, the melt–albedo feedback is impacting

the thinning over the whole ice sheet (Figure 4 (C)). However, the most important contribution remains in the south-west of Greenland, with additional 300 m thinning compared to RCP8.5 α_{1990} .

4.3 An upper limit for ice loss through extreme surface darkening

As a next step, the upper limit of the melt–albedo feedback is explored via prescribing summer albedos equal to the bare ice

5   albedo over the whole ice sheet in each year (see details in Section 2.6). First, the effect of such a surface darkening is explored without any temperature forcing in the Ctrl α_{dark} scenario. In this experiment approximately linear mass loss is observed, with a rate of 8 mm SLE per decade (see Fig. 4 (A)) and induces ice losses of 8.3 cm until 2100 and 20.1 cm until 2300. The condition that the local monthly mean air temperature needs to be higher than -6.5 °C to allow melt, prevents further melting in the ice sheet's interior. Topographic changes together with the temperature-lapse rate feedback increase the melt area slowly, but do

10   not have a major impact over the 300 years. Note that this extreme darkening Ctrl α_{dark} scenario alone induces more ice loss than the RPC2.6 α_{1990} scenario (see Fig. 4 and table 1).

The RCP2.6 α_{dark} experiment combines the extreme summer darkening with the RCP2.6 temperature anomaly, thereby increasing ice losses from the RCP2.6 α_{1990} experiment by more than a factor of four in comparison to the α_{1990} experiments (Figure 4 and Table 1). This corresponds to a more than fourfold increase in ice losses. The darkening together with the

15   moderate temperature increase induces an expansion of the melt zone and thus strong melt in areas that are not affected in the Ctrl or RCP2.6 experiments. The ice-volume evolution in the RCP2.6 experiment is closer to the lower than to the upper bound of the melt–albedo feedback.

In the RCP8.5 α_{dark} experiment the summer darkening leads to an increase in ice loss of 214 % in 2100 and 77 % in 2300 in comparison to the no-feedback RCP8.5 α_{1990} experiment (see Fig. 4 and table 1). The strong shock of albedo darkening is

20   particularly relevant when overall temperature increases are still low. In contrast to the RCP2.6 α_{dark} experiment, where the additional mass losses increase with time, here the relative impact of extreme summer darkening decreases on long time scales. As the warming progresses the temperature becomes a more important driver to melt.

Reducing the frequency of the darkening in the RCP2.6 α_{dark} and RCP8.5 α_{dark} experimens linearly reduces the difference in mass loss between the dark RCP and the RCP experiments (see Appendix Figure B1). Reducing the length of the dark period

25   from the whole summer (i.e. June, July and August) to only one month reveals that the month of June is most sensitive to additional darkening, inducing more than half of the additional ice losses between the RCP8.5 and the RCP8.5 α_{dark} experiments (see Appendix Figure B1).

4.4 Exploring uncertainty in albedo-change driven ice losses

The standard parameters for the albedo parameterization used in the RCP2.5 and the RCP8.5 experiments provide the best fit

30   to the MARv3.11 data over the historic period. However, the corridor for possible contributions of the melt–albedo feedback is large, therefore we test how changes in the albedo parameterization affect the ice losses driven by albedo changes. The albedo parametrization can affect the strength of the melt–albedo in two ways: first by changing α_{min} , the lowest albedo possible, and second by changing the sensitivity of albedo to melt via the slope in Equation (7). To ensure that the subsequent mass

changes are not primarily due to model drift, they are corrected by a Ctrl experiment without warming but with otherwise same parameters.

A decreased value of α_{min} does not affect regions where melt rates are below 14 m/yr. Consequently, strong melt rates are necessary to observe its impacts: in the RCP8.5 α_{min} simulations with $\alpha_{\mathrm{min}} = 0.4$ the lowered α_{min} value causes additional
5   5.3 cm of ice loss in 2300 (compared to RCP8.5) and the RCP8.5 α_{min} simulations with $\alpha_{\mathrm{min}} = 0.3$, it causes additional 16 cm until 2300 (Figure 5 (A)).

In contrast to the α_{min} experiments, changing the slope in the albedo parameterization in Equation (7) affects the sensitivity of the albedo to melt already at low melt rates. In the Ctrl α_{hs} experiment, the ice sheet loses 10 cm SLE until 2300 from the increase in the albedo sensitivity alone, indicating that this is not consistent with the standard parameters presented in Sect. 2.5.
10 We test thus the mass losses of the warming scenarios with respect to the Ctrl α_{hs} experiment, in order to explore the interplay of an increased melt–albedo feedback and warming.

The additional effect of the increased sensitivity on ice-volume evolution depends on the warming scenario. The RCP2.6 α_{hs} experiment with moderate warming is affected by a more sensitive albedo parameterization, with up to 40 % increases in ice loss until 2300 with respect to the RCP2.6 experiment (see Figure 5). In contrast, the additional mass loss in the RCP8.5 α_{hs}
15 is lower with +6 % in 2300 compared to the RCP8.5 scenario. This is because already in the RCP8.5 scenario melt is quickly high enough to reach the minimal albedo. Once the minimal albedo is reached, further increase in melt rates does not affect the albedo any more, thus the melt is not affected by the stronger feedback any more.

If the sensitivity of albedo to melt is reduced, the ice sheet in the the Ctrl α_{ls} experiment shows slight mass gains (4 cm over 300 years). The lower sensitivity mitigates mass losses from both, the RCP2.6 α_{ls} and the RCP8.5 α_{ls} experiments, with
20 8.3 cm and 29.4 cm less mass loss until 2300 respectively. However, even with the reduced melt–albedo feedback the ice losses increase by approximately one third when compared to the α_{1990} experiment without albedo-melt feedback.

5   Discussion

We have presented an implementation of a simple version of the diurnal energy balance model (dEBM-simple) as a module in the Parallel Ice Sheet Model PISM. Using this model we evaluate how changes in albedo impact future mass loss of the
25 Greenland Ice Sheet under the RCP2.6 and the RCP8.5 warming scenarios.

5.1   Implementation and validation

In dEBM the surface melt is calculated as a function of near-surface air temperature and shortwave downward radiation. A first version of the dEBM was tested and validated in Krebs-Kanzow et al. (2018) and a full version was presented in Krebs-Kanzow et al. (2020). dEBM-simple adapts the approach taken in Krebs-Kanzow et al. (2018) and adds additional modules to calculate
30 the albedo as a function of melt, as well as the shortwave downward radiation. Therefore the only inputs needed to compute the melt rate are two-dimensional near-surface temperature fields including the yearly cycle, and further a precipitation field in order to complete the climatic mass balance. This approach makes the model as input-friendly as a temperature-index model

such as the classical positive degree day model, but with the advantage to capture the melt–albedo feedback. The dEBM-simple surface mass balance module can therefore be used with PISM in a standalone setting to simulate past and future ice-sheet evolution, requiring only a temperature field, a precipitation field, and the time-series of the temperature anomaly as inputs. As PISM is an open-source project, the module can easily be expanded or implemented in other standalone ice-sheet

5   models.

Being a simple model, dEBM-simple does not fully resolve the spatial pattern and temporal evolution of melt over the Greenland Ice Sheet, the melt rates are slightly overestimated towards the beginning of the melt season (June) and underestimated towards the end of the melt season (August) and at the margins of the ice sheet. However, the total yearly melt rates match well with those of MAR over the period 1958-2019 and on this timescale the skill of the model is comparable to the dEBM

10   (Krebs-Kanzow et al., 2020). The exception of the extreme melt in the years 2012 and 2019, where dEBM-simple clearly underestimates melt rates, are related to changes in cloud cover or blocking events (Delhasse et al., 2021; Hanna et al., 2014; Hofer et al., 2017), which are not captured by the parameterization of the transmissivity of the atmosphere.

Increased insolation values like during the Eemian increase the melt on average by 97 Gt/yr under otherwise same conditions. This is in line with the findings of Van De Berg et al. (2011). While this is only an approximation with several strong

15   assumptions, e.g. the present-day topography of the ice sheet is preserved and we did not apply changes in the temperature, it illustrates the possibility of extending this model to paleo timescales with relatively low efforts.

The implemented parametrization for albedo is based on a phenomenological relation of albedo to the melt rate. It is a coarse representation of the effects, which are important for the albedo of snow and ice, such as the grain size of snow, surface water and melt ponds, impurities on snow or ice (e.g. black carbon or algae) or any dependence on the spectral angle or the cloudiness

20   condition of the sky. Moreover, it neglects the impact of the snow-cover thickness, which might mitigate melt-driven reduction in albedo after a winter with heavy precipitation (Box et al., 2012). Similarly, the parametrization introduced for the shortwave downward radiation does not take into account temporal or spatial patterns. The inter-annual variability of the cloudiness over Greenland and blocking events can therefore not be represented with this approach.

However, the introduced parametrizations do not introduce a systematic bias or a large additional error in comparison to

25   a purely diagnostic mode of dEBM-simple, where instead of parametrized albedo and shortwave downward radiation the 2D fields of MAR output are used to calculate the melt rates (see Figure A3), while all other parameters are kept constant.

5.2   Sensitivity of the Greenland Ice Sheet to warming and surface darkening

In this manuscript we use the PISM-dEBM-simple model in order to assess the influence of albedo changes and surface warming on the Greenland Ice Sheet. The simple surface mass balance model allows a first estimate of the influence of the

30   melt–albedo feedback on the future evolution of the Greenland Ice Sheet in two temperature scenarios: moderate warming RCP2.6, a scenario compatible with the Paris Agreement, and high warming RCP8.5, a worst-case scenario. Experiments with a fixed yearly cycle of the albedo suppress the melt–albedo feedback and thus serve as a lower bound to future ice losses. In contrast, the extreme scenario in the α_{dark} experiments with the surface albedo lowered to the bare ice value over the whole ice

sheet for the months June, July and August serves as an upper bound for future melt through the melt–albedo feedback. The experiments with adaptive albedo serve as a more realistic estimate of future mass losses.

This experimental design allows to attribute ice losses to the melt–albedo feedback. Overall we find that the melt–albedo feedback has a strong influence on melt under future warming. For example in the RCP2.6 scenario, the ice loss almost
5   doubles through the albedo feedback (compare RCP2.6 with RCP2.6 α_{1990}). Moreover, the relative amount of ice loss driven by changes in albedo keeps increasing over time. In contrast, the share of melt driven by albedo changes is lower in the high temperature RCP8.5 scenario and decreases as the temperature increases, indicating that temperature is a more important driver under these conditions. Note however, that the absolute increase in mass loss through the feedback is higher for RCP8.5 than for RCP2.6. We also find that extreme darkening alone, without any temperature anomaly, can initiate mass losses comparable
10   to the RCP2.6 scenario.

Moreover, the interaction between the extreme darkening and warming initiates additional ice losses. In particular the RCP2.6 α_{dark} scenario loses 23 % more mass until 2300 than the sum of RCP2.6 and the Ctrl α_{dark} simulations, suggesting that other feedbacks, such as the melt–elevation feedback, enhance the mass loss of the RCP2.6 α_{dark} scenario.

In this setup the melt–elevation feedback has a smaller impact on ice losses than the melt–albedo feedback: experiments
15   which neglect the melt–elevation feedback (here paramterized through the atmospheric temperature lapse rate of -6K/km) lose 18 % less mass in the RCP2.6 T_{noLR} scenario and 13% less in the RCP8.5 T_{noLR} scenario until 2300, respectively (see Figure C1). This is in line with previous studies (Le clec'h et al., 2019) and suggests that the melt–elevation feedback, although weaker than the melt–albedo feedback, should not be neglected on the time scale of several centuries.

In this study, we assume simplified representations of both the melt–elevation and the melt–albedo feedbacks. However,
20   certain effects such as the feedbacks between the topography of the ice sheet and the atmospheric conditions which affect the surface mass balance cannot be expressed in the atmospheric temperature lapse rate alone. Similarly, the albedo is affected not only by melt, but also the sky conditions, snow events, and impurities. While PISM-dEBM-simple is computationally efficient and represents the ice dynamics well, it cannot compete with an explicit process-based snow-pack model as used by the regional climate models MAR or RACMO (Le clec'h et al., 2019; Kuipers Munneke et al., 2011) or represent the effect of
25   summer snowfall on albedo (Noël et al., 2015). Moreover, here the melt–albedo feedback is represented by a relation linear at low melt rates and obtained from a MAR simulation over the historic period 1958-2019. This relation might not apply under future warming. Therefore we test uncertainties related to the albedo parameterization with the resulting mass losses lying in the corridor between the lower bound, i.e., the no-feedback scenario, and the upper bound, i.e., the extreme darkening scenario. Further analysis of the influence of the melt–albedo feedback with models that fully resolve the firn layer would be helpful to
30   analyse processes that are neglected or simplified in this manuscript.

In observations, long-lasting albedo changes are already found as a consequence of heat waves which initiate strong surface melt (Nghiem et al., 2012; Tedesco and Fettweis, 2020). While the regions with the most rapid darkening in Greenland are located in the ablation zones, ice-sheet wide melt events trigger albedo changes over the whole ice sheet (Tedesco et al., 2016). Studies suggest that heat waves in the Arctic may become more frequent with future warming (Dobricic et al., 2020),
35   with still unknown consequences to ice-sheet melt and albedo. Currently, there are no explicit albedo projections, which

take all processes and feedbacks like the distribution of surface meltwater, algae growths, dust deposition, and dust meltout into account. While PISM-dEBM-simple does not explicitly model all these processes, it adds a tool to explore albedo-change scenarios and their influence on the future evolution of the ice sheet in a numerically efficient way, which takes the ice dynamics into account.

6   Conclusion

The module dEBM-simple is implemented in the open-source Parallel Ice Sheet Model PISM and allows to capture albedo and insolation as well as temperature-driven melt in standalone ice-sheet simulations. Due to its simplicity it can be used to perform large-scale ensemble studies or long-term simulations over centuries to millennia. The source code is fully accessible and documented, as we want to encourage improvements and implementation in other ice-sheet models. This includes the adaption to other ice sheets than the Greenland Ice Sheet.

Using PISM-dEBM-simple we find that the melt–albedo feedback can lead to additional 12 cm sea-level equivalent of mass loss in RCP2.6 and additional 70 cm in RCP8.5 until the year 2300. While our experiments rely on a simple parameterization of albedo with surface melt, they show that future albedo changes can make an important contribution to Greenland's future mass loss.

Code and data availability.   The PISM source code including the dEBM-simple module is freely available through https://github.com/mariazeitz/pism/tree/pik/dEBM_dev. The code of the regional climate model MAR is available through https://mar.cnrs.fr/. The MAR data is available at ftp://ftp.climato.be/fettweis/MAR v3.11/Greenland/ERA_1958-2019-10km/monthly_1km/. The CMIP5 datasets for the RCP2.6 and the RCP8.5 warming scenarios are available through https://esgf-node.llnl.gov/search/cmip5/.

Appendix A: Parametrizations for standalone ice-sheet models

A1   Parametrization of albedo as a function of melt

Albedo is complicated to parametrize correctly, because of its dependence on a number of factors: the snow or firn albedo depends on grain size, impurities, surface water, refrozen ice, compaction, sky conditions and spectral angle, while the ice albedo depends on impurities, surface water, sky conditions and spectral angle. Here we aim for a very simple phenomenological parametrization of albedo, which is good enough to be valid on large spatial scales and on long time scales. Only the broadband albedo is parametrized here, assuming that the average cloudiness of the sky does not change over long time scales. Further, it is assumed that grain size and surface water can be summarized in a single dependence of the albedo on the melt rate. In the MAR v3.11 dataset, a negative correlation of albedo with melt is found (see Figure A1). The average relation over the months June, July and August in the period of 1958-2019 can be best described by the linear relation $\alpha = -0.025\,\text{yr/m} \cdot m + 0.82$, indicated by the dashed orange lines in Figure A1. The intersection with the y-axis is interpreted as average snow albedo. At

Table A1. Variables used in dEBM-simple

Name	Variable	Unit
z	ice surface elevation	km
α_s	albedo	
$\bar{T}$	monthly average near surface temperature	°C
T_{eff}	cumulative temperature exceeding the melting point	°C
τ_α	transmissivity of the atmosphere	
$\bar{S}_\Phi$	TOA insolation, averaged over Δt_Φ	W/m^2
SW	shortwave downward radiation at the surface	W/m^2
M	melt rate	kg m^{-2}s^{-1}
Δt_Φ	time period with sun above elevation angle Φ	s
$\bar{Q}^{\text{day}}$	daily average TOA insolation	W/m^2
ϵ, ω, e	orbital parameters	°, °,
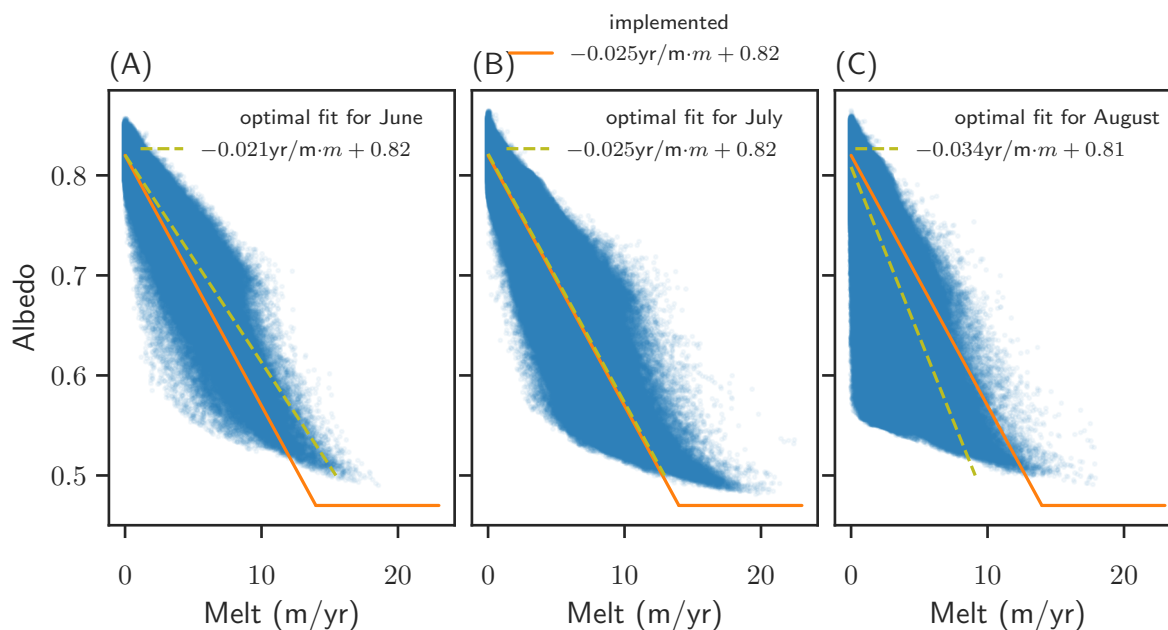
Figure A1. Fit for albedo parametrization Albedo vs. melt of June (A), July (B) and August (C) over the period 1958 - 2019 in the MAR v3.11 dataset. Each dot represents values in one cell of the ice sheet, averaged over a month. Orange lines show the parametrization with parameters as used in PISM. Light green lines show the best linear fit for each month, with the parameters given in the legend.

Table A2. Parameters used in dEBM-simple

Name	Parameter	Value	Reference
ρ_w	fresh water density	$1000\,\mathrm{kg/m^3}$	
L_m	latent heat of fusion	$3.34 \cdot 10^5\,\mathrm{J/kg}$	
c_1, c_2	dEBM parameters	29, -93	optimized
S_0	solar constant	$1367\,\mathrm{W/m^2}$	Liou (2002)
Φ	minimal elevation angle for melt	$17.7°$	Krebs-Kanzow et al. (2018)
σ	standard deviation of daily temperature	5K	
a, b	parameters for transmissivity	$0.57, 0.0037\mathrm{km}^{-1}$	optimization
$\alpha_{\mathrm{max}}, \alpha_{\mathrm{min}}$	maximal and minimal albedo values	0.82, 0.47	optimization
c	slope in albedo parametrization	$-0.025\,\mathrm{yr/m}$	optimization
γ	atmospheric temperature lapse rate	$-6\,\mathrm{K/km}$	typical value
T_{min}	temperature threshold for melt	$-6.5°\mathrm{C}$	Krebs-Kanzow et al. (2018, 2020)

very high melt rates the albedo is less sensitive to additional increases with melt, which might be caused when e.g. the snow cover disappeared and bare ice is exposed. In this parametrization we introduce a lower limit to the albedo such that it can not be lower than 0.47 (approximately the value for bare ice (Gardner and Sharp, 2010; Bøggild et al., 2010)). This value is lower than the MAR value for bare ice, but in line with MODIS and RACMO at the ice margin, where impurities can accumulate

5 (Noël et al., 2018; van Dalum et al., 2020; Stroeve et al., 2013). There is a large variance in how sensitively albedo is related to melt, which is due to both, spatial and temporal (intra-annual as well as inter-annual) variability. However, a clear long-term trend of how the albedo depends on surface melt could not be established. In July, the albedo is on average less sensitive to melt, with an average slope of $-0.021\,\mathrm{yr/m}$, in June the monthly fit is identical to the the whole summer and in August the albedo decreases on average more strongly with melt, corresponding to a slope of $-0.034\,\mathrm{yr/m}$. In addition, in August there is a broad

10 distribution of albedo values at zero melt, ranging from approximately 0.57 to the fresh snow value, which underlines that the correct albedo depends not only on the current condition but also on the melt during the past months. In order to estimate the sensitivity of future ice evolution to the exact parameters of the albedo parameterization, we vary the slope of the albedo over a broad range, by taking the double or half slope found with the linear regression, here indicated with the grey lines.

We tested discrete albedo classes, that are successfully used in other models (e.g. Krebs-Kanzow et al. (2020); Krapp et al.

15 (2017); Robinson et al. (2010)). In our implementation, we found that the continuous relation of albedo to melt was better to predict melt. We found that it is also better suited than a parametrization with the snow thickness, successfully used by many models as well (Krapp et al., 2017). The parameterization with snow thickness did lead to too low albedo values and thus too high melting in North West Greenland, where precipitation is generally low. Our approach comes with the caveat, that the snow thickness is not considered for the calculation of the albedo, although observations suggest that increased winter snow

20 can mitigate summer melt due to the higher albedo of the snow (Box et al., 2012; Riihelä et al., 2019).

A2 Parametrization of shortwave downward radiation

Shortwave downward radiation that reaches the ice sheet's surface depends on the incoming radiation at the top of the atmosphere, the solar zenith angle, the surface altitude, and the cloud cover. In order to get the most correct estimate of shortwave downward radiation at the ice sheet's surface, it would be ideal to know the monthly average cloud cover. Since here, we aim for a parametrization, which makes the model as simple as a temperature index model concerning the inputs needed, we instead parametrize the transmissivity of the atmosphere with the assumption that the average cloud cover does not change, neither during the summer months nor on longer time scales. Following Robinson et al. (2012) we assume that the transmissivity is solely a function of the surface altitude. In order to get a best estimate to this relation, the top of the atmosphere (TOA) radiation, which depends only on season and latitude, is compared to the MAR output for shortwave downward radiation. The daily average TOA radiation $\bar{Q}^{\mathrm{day}}$ is described by Equation (4). The local shortwave downward radiation SW would then be

$$SW = \bar{Q}^{\mathrm{day}} \cdot \tau_\alpha.$$

A linear relation of the transmissivity to the surface altitude is given by

$$\tau_\alpha = a + b \cdot z$$

with the surface elevation in meters z and the fit parameters a and b. The linear fit for the shortwave downward radiation from TOA insolation was obtained from a linear regression of MAR v3.11 data averaged over June, July and August from 1958 to 2019 (see Figure A2).

5   Because melting occurs predominantly over the summer months June, July and August, we derive the average transmissivity of the atmosphere based on the transmissivity calculated in MAR in June, July and August. The best fit over these three months simultaneously is obtained with $a = 0.57$ and $b = 0.037$ 1/km, as indicated by the orange dashed line in Figure A2. A seasonality can be observed, the transmissivity is on average higher in June ($a = 0.61$ and $b = 0.026$ 1/km) than in July ($a = 0.57$ and $b = 0.040$ 1/km) and August ($a = 0.053$ and $b = 0.046$ 1/km).

10 For simulations under paleo-conditions, changes in orbital parameters affect the insolation at the top of the atmosphere and the trigonometric expansion used under present day conditions (see Section 2.3.1) does not hold. The declination angle is then described by $\sin \delta = \sin(\epsilon) \sin(\lambda)$ and the sun-earth distance

$$\left(\frac{\bar{d}}{d} \right)^2 = \frac{(1 + e \cos(\lambda - \omega))^2}{(1 - e^2)^2} \tag{A1}$$

with the oblique angle ϵ, the eccentricity e, the precession angle ω and the true longitude of the earth λ. The orbital parameters

15 e, ϵ and ω are given in the input, while λ varies over the time of the year and is computed internally using an approximation of Berger (1978) :

$$\lambda = \lambda_m + \left(2e - \frac{e^3}{4} \right) \sin(\lambda_m - \omega) + \frac{5}{4} e^2 \sin(2(\lambda_m - \omega)) + \frac{13}{12} e^3 \sin(3(\lambda_m - \omega)), \tag{A2}$$
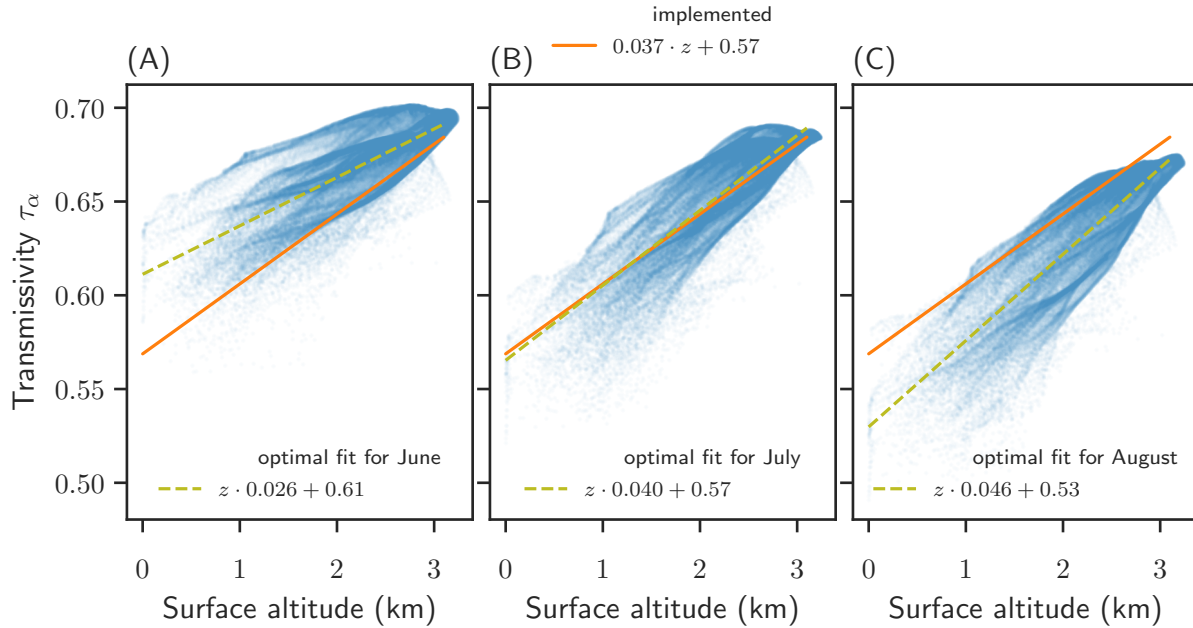
Figure A2. Fit for the parametrization of transmissivity Shortwave downward radiation vs. surface altitude in June (A), July (B) and August (C) over the period 1958 - 2019 in the MAR v3.11 dataset. Each dot represents values in one cell of the ice sheet, averaged over a month. Orange lines show the parametrization with parameters as implemented, which is the best fit over the three months, June, July, and August together. Light green lines show the best linear fit for each month, with the parameters given in the legend.

with

$$\lambda_m = -2 \left(\left(\frac{e}{2} + \frac{e^3}{8}\right) \left(1 + \sqrt{1-e^2}\right) \sin(-\omega) - \frac{e^2}{4} \left(\frac{1}{2} + \sqrt{1-e^2}\right) \sin(-2\omega) + \frac{e^3}{8} \left(\frac{1}{3} + \sqrt{1-e^2}\right) \sin(-3\omega) \right) + \Delta\lambda$$

$\Delta\lambda = 2\pi(\text{day} - 80)/\text{days per year}.$

Here $\lambda = 0$ at the spring equinox.

5   A3   Validation of parameterization

In order to asses the validity of the parameterizations in PISM-dEBM-simple, the yearly melt with the fully parameterized model, as shown in Figure 1, is compared to the yearly melt of a diagnostic analysis of the dEBM-simple with otherwise fixed parameters. Instead of computing the albedo and the shortwave downward radiation internally, monthly fields of those variables from the MAR v3.11 date are given as input to compute the melt rates via Equation (1) with the same parameters 10 c_1 and c_2. While the diagnostic experiment performs better in the extreme melt years 2012 and particularly 2019, we find an increased mismatch, in particular in the 1970s and a resulting larger root mean square error. This can be attributed to the fact, that the parameters c_1 and c_2 were optimized for a low temporal and spatial RMSE with the parametrizations for albedo and
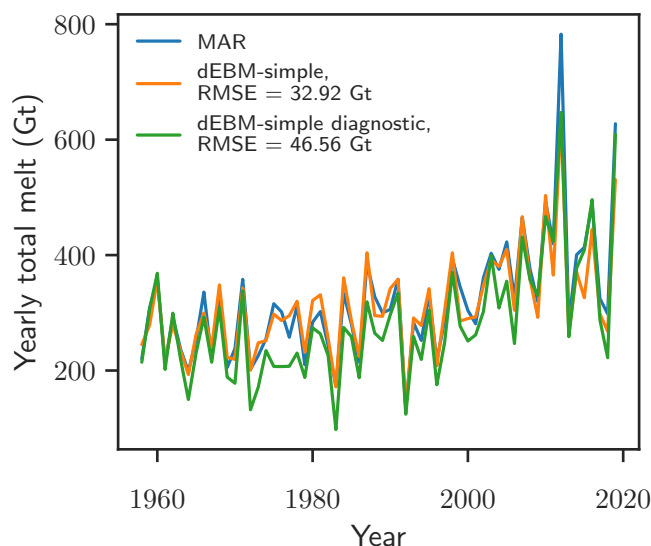
Figure A3. Yearly total melt of the Greenland Ice Sheet as calculated with MAR (blue), diagnosed with the fully parameterized PISM-dEBM-simple simulation (orange), which uses only the monthly 2D temperature fields as input, and diagnosed with a non-paramterized diagnostic dEBM-simple version, which takes the 2D-temperature field, the shortwave downward radiation and the albedo as inputs. The root mean square error for the individual time-series are given in the legend.

transmissivity as desribed above. c_1 and c_2 differ from Krebs-Kanzow et al. (2018) and from an optimal value for the diagnostic melt rate.

Appendix B: Sensitivity to the darkening scenario

In order to test how the results are impacted by a shorter darkening period or even stronger albedo forcing, we study the upper
5 limit RCP8.5 α_{dark} scenario in greater detail.

Shortening the darkening period to only one month reduces, as expected, the impact of darkening. Moreover, it reveals which months are the most vulnerable to darkening. In particular, we observe that darkening in June leads to the highest mass losses (see dash-dotted line in Figure B1 (A)). Darkening in June alone leads to 9.6 cm additional mass loss in 2100 and to 14.8 cm additional mass loss in 2300 compared to the Warming RCP8.5 scenario without darkening. In contrast, darkening in only July
10 or August has a less significant effect, with 4.3 cm and 1.4 cm additional mass loss in 2100 and 7.5 cm and 5,4 cm in 2300. On the one hand this might be caused by the larger insolation and longer days during the month of June. In June average daily insolation at latitudes above 60°N is approximately 7 % larger than in Juny and 50 % larger than in August. Moreover, due to the high melt in the Warming RCP8.5 scenario, albedo values are already low in July and August, even without darkening.
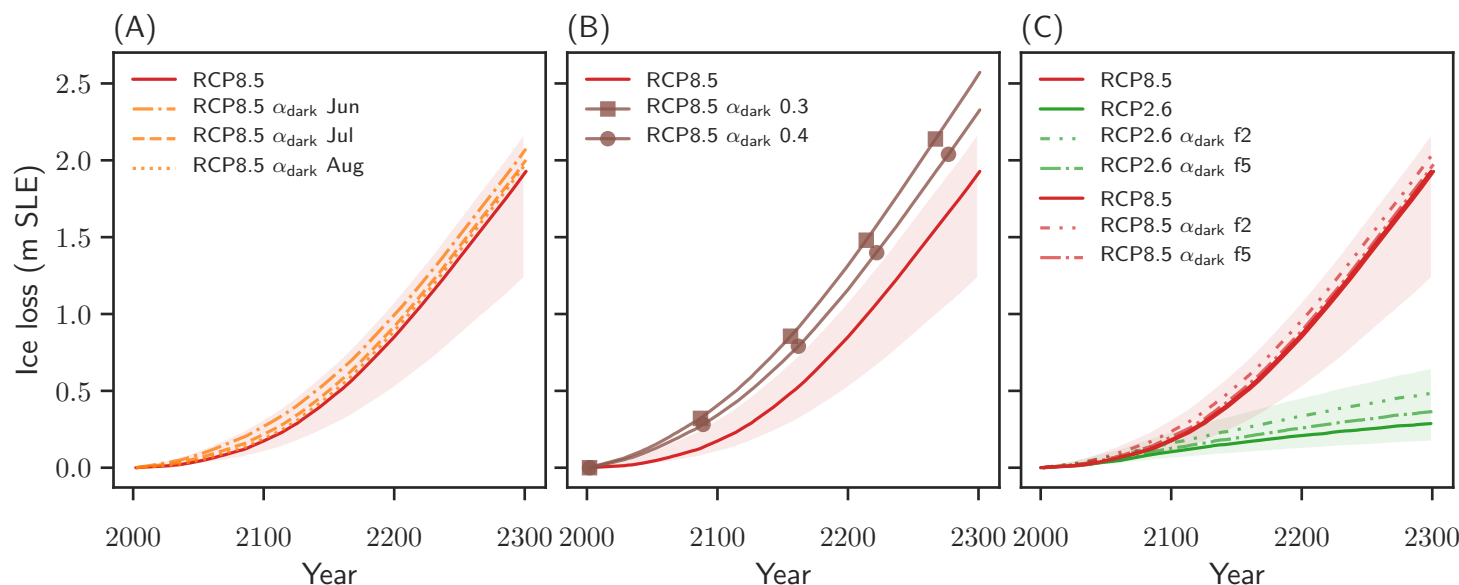
Figure B1. Sensitivity to the darkening scenario Ice volume evolution for different implementations of the darkening scenario. The envelopes of minimal and maximal mass loss, given by α_{1990} and α_{dark} experiments, and the RCP simulations with standard parameters are shown for reference. (A) Period of extreme darkening in the α_{dark} scenario are shortened to one month (orange broken lines). (B) The albedo value for extreme summer darkening is lowered to 0.3 (brown line with square markers) or 0.4 (brown line with circle markers). (C) Reducing the frequency of extreme darkening summers to every 2 (f2) and every 5 years (f5).

Using an albedo value which is lower than the value for bare ice leads to increased ice losses. An albedo value of 0.4 instead of 0.47 over the whole ice sheet increases ice loss by additional 16 % or 4.6 cm by the year 2100 and by additional 8 % or 17 cm by the year 2300 compared to the RCP8.5 α_{dark} scenario. An even lower albedo value of 0.3 increases ice losses by additional 37 % or 11 cm by 2100 and by additional 19 % or 41 cm by 2300 compared to the RCP8.5 α_{dark} scenario.

5   Reducing the frequency of dark summers to every 2 years leads to additional mass losses which are approximately half of the additional mass losses caused by the darkening in every year for both warming scenarios. A darkening frequency of every 5 years leads to additional mass losses of about 20 % of the additional mass loss with darkening in every year. This suggests that, at least on time scales of 300 years, the effects of more or less frequent darkening remain linear.

Appendix C: Effect of the melt–elevation feedback

10   The melt–elevation feedback is generally represented in all experiments by adjusting surface temperatures with height changes by 6 K/km. The influence of the feedback on the simulations is tested by switching off this lapse-rate correction, with the resulting mass loss shown in Fig. C1.
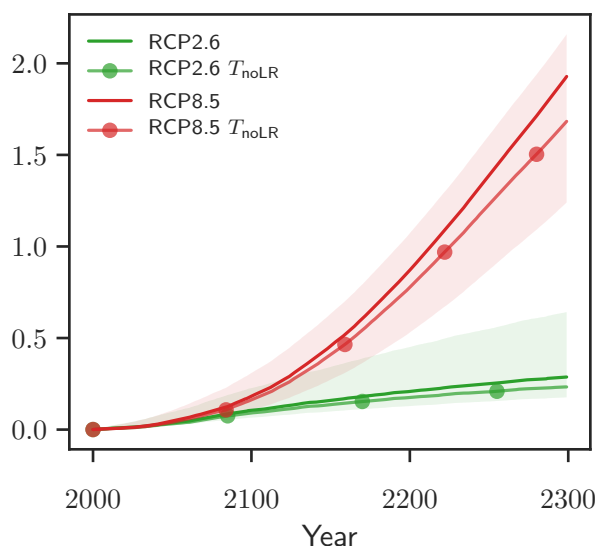
Figure C1. Impact of the melt–elevation feedback. PISM-dEBM-simple simulations of the Greenland Ice Sheet with RCP2.6 (green lines) and RCP8.5 (red lines) warming. Dark solid lines take the melt–elevation-feedback through the atmospheric temperature lapse rate into account. Shaded lines with markers neglect the melt–elevation feedback and assume a zero atmospheric temperature lapse rate.

Author contributions. MZ implemented the dEBM-simple module with the parameterizations for albedo and shortwave downward radiation and performed the analysis. RW conceived the study. JB contributed the initial state for PISM simulations. UKK developed the dEBM model, the basis for dEBM-simple, and provided support with the setup. MZ and RR designed and wrote the manuscript with input and feedback from all coauthors.

5   *Competing interests.* The authors declare that they have no conflict of interest

Acknowledgements. M.Z. and R.W. are supported by the Leibniz Association (project DOMINOES). M.Z. and R.R. are supported by the Deutsche Forschungsgemeinschaft (DFG) by grant WI4556/3-1. R.R. was further supported through the TiPACCs project that receives funding from the European Union's Horizon 2020 Research and Innovation program under grant agreement no. 820575. J.B. is supported by the Deutsche Forschungsgemeinschaft through project 422877703. R.W. is grateful for support by the Deutsche Forschungsgemeinschaft
10 (DFG) through grants WI4556/3-1 and WI4556/5-1 and by the PalMod project (FKZ: 01LP1925D), supported by the German Federal Ministry of Education and Research (BMBF) as a Research for Sustainability initiative (FONA). Development of PISM is supported by NASA grant NNX17AG65G and NSF grants PLR-1603799 and PLR-1644277. The authors gratefully acknowledge the European Regional Development Fund (ERDF), the German Federal Ministry of Education and Research and the Land Brandenburg for supporting this project by providing resources on the high performance computer system at the Potsdam Institute for Climate Impact Research.

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